Prediction of a Rift Valley fever outbreak

Assaf Anyamba[a,1], Jean-Paul Chretien[b,2], Jennifer Small[a], Compton J. Tucker[a], Pierre B. Formenty[c], Jason H. Richardson[d,3], Seth C. Britch[e], David C. Schnabel[f], Ralph L. Erickson[b], and Kenneth J. Linthicum[e]

[a]National Aeronautics and Space Administration Goddard Space Flight Center, Biospheric Sciences Branch, Code 614.4, Greenbelt, MD 20771; [b]Department of Defense Global Emerging Infections Surveillance and Response System, Division of Preventive Medicine, Walter Reed Army Institute of Research, 503 Robert Grant Avenue, Silver Spring, MD 20910; [c]Biorisk Reduction for Dangerous Pathogens, Communicable Diseases Cluster/Department of Epidemic and Pandemic Alert and Response, World Health Organization, 20 Avenue Appia, CH-1211, Geneva 27, Switzerland; [d]Department of Entomology and Vector-borne Disease, United States Army Medical Research Unit-Kenya, APO AE 09831-4109; [e]United States Department of Agriculture–Agricultural Research Service Center for Medical, Agricultural, and Veterinary Entomology, 1600 SW 23rd Drive, Gainesville, FL 32608; and [f]United States Army Medical Research Unit-Kenya, Unit 64109 Box 401 APO AE 09831-4109

Edited by B. L. Turner, II, Arizona State University, Tempe, AZ, and approved November 14, 2008 (received for review July 11, 2008)

El Niño/Southern Oscillation related climate anomalies were analyzed by using a combination of satellite measurements of elevated sea-surface temperatures and subsequent elevated rainfall and satellite-derived normalized difference vegetation index data. A Rift Valley fever (RVF) risk mapping model using these climate data predicted areas where outbreaks of RVF in humans and animals were expected and occurred in the Horn of Africa from December 2006 to May 2007. The predictions were subsequently confirmed by entomological and epidemiological field investigations of virus activity in the areas identified as at risk. Accurate spatial and temporal predictions of disease activity, as it occurred first in southern Somalia and then through much of Kenya before affecting northern Tanzania, provided a 2 to 6 week period of warning for the Horn of Africa that facilitated disease outbreak response and mitigation activities. To our knowledge, this is the first prospective prediction of a RVF outbreak.

El Niño | Horn of Africa | vegetation index | risk mapping | zoonotic disease

Rift Valley fever is a viral disease of animals and humans that occurs throughout sub-Saharan Africa, Egypt, and the Arabian Peninsula. Outbreaks of the disease are episodic and closely linked to climate variability, especially widespread elevated rainfall that facilitates Rift Valley fever (RVF) virus transmission by vector mosquitoes (1–3). A RVF outbreak in 1997–1998 was the largest documented outbreak in the Horn of Africa and involved 5 countries with a loss of ≈100,000 domestic animals, ≈90,000 human infections (4), and had a significant economic impact due to a ban on livestock exports from the region (5).

The 1997–1998 epizootic/epidemic was important in explicitly confirming the links between episodic RVF outbreaks and El Niño/Southern Oscillation (ENSO) phenomena, which are manifested by episodic anomalous warming and cooling of sea-surface temperatures (SSTs) in the eastern equatorial Pacific Ocean (2). Other vector-borne diseases have also been associated with ENSO-related variations in precipitation (6–11). Concurrently, anomalous warm SSTs in the equatorial eastern-central Pacific Ocean region and the western equatorial Indian Ocean result in above-normal and widespread rainfall in the Horn of Africa (2). This excessive rainfall is the principal driving factor for RVF outbreaks there (1, 3).

Each of the 7 documented moderate or large RVF outbreaks that have occurred in the Horn of Africa (Fig. S1) over the last 60 years have been associated with ENSO-associated above-normal and widespread rainfall (Fig. S2) (2, 12). Exceptions to this association can occur, but are localized, such as the 1989 Kenyan outbreak that was related to local heavy rainfall at the focus of the outbreak (13, 14). Earth observation by satellite remote sensing over the last ≈30 years has enabled systematic mapping of driver indicators of climate variability including SST patterns, cloud cover, rainfall, and ecological indicators (primarily vegetation) on a global scale at high-temporal and moderate spatial resolutions (2, 15–18). These systematic observations of the oceans, atmosphere, and land have made it possible to evaluate different aspects of climate variability and their relationships to disease outbreaks (16), in addition to providing valuable long-term climate and environmental data (Table S1).

In most semiarid areas, precipitation and green vegetation abundance are major determinants of arthropod and other animal population dynamics. There is a close relationship between green vegetation development and breeding and upsurge patterns of some insect pests and vectors of disease such as mosquitoes and locusts (1, 17–19). The successful development and survival of mosquitoes that maintain, transmit, and amplify the RVF virus is closely linked with rainfall events, with very large populations of mosquitoes emerging from flooded habitats after above-normal and persistent rainfall (20–22). The close coupling between ENSO, rainfall, vegetation growth, and mosquito life cycle dynamics, and improvements in seasonal climate forecasting have provided a basis for using satellite time series measurements to map and predict specific areas at elevated risk for RVF activity.

Retrospective analysis of a satellite-derived time series vegetation measurements of photosynthetic activity, known as the normalized difference vegetation index (NDVI) (23), has shown that such data, in combination with other climate variables, can be used to map areas where RVF occurred (1, 2, 12, 16, 20). In 1999, the Department of Defense Global Emerging Infections, Surveillance and Response System, in collaboration with National Aeronautics and Space Administration (NASA) Goddard Space Flight Center and the United States Department of Agriculture, initiated a program to systematically monitor and map areas at potential risk for RVF outbreaks. The program focuses on sub-Saharan Africa, the Nile Basin in Egypt, and the western Arabian Peninsula, with an emphasis on the RVF endemic region of the Horn of Africa (Fig. S1). The risk monitoring and mapping system is based on the analysis and interpretation of several satellite derived observations of SSTs, cloudiness, rainfall, and vegetation dynamics (12). These data

SUSTAINABILITY SCIENCE

Author contributions: A.A., J.-P.C., C.J.T., R.L.E., and K.J.L. designed research; A.A., J.-P.C., J.S., C.J.T., P.B.F., J.H.R., S.C.B., D.C.S., and K.J.L. performed research; A.A., J.S., and K.J.L. contributed new reagents/analytic tools; A.A., J.S., and S.C.B. analyzed data; and A.A., J.-P.C., J.S., C.J.T., P.B.F., J.H.R., S.C.B., D.C.S., R.L.E., and K.J.L. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

[1]To whom correspondence should be addressed. E-mail: asaph.anyamba-1@nasa.gov.

[2]Present address: Division of Preventive Medicine, Walter Reed Army Institute of Research, 503 Robert Grant Ave., Silver Spring, MD 20910.

[3]Present address: Armed Forces Research Institute of Medical Sciences, United States Army Medical Component, 315/6 Rajvithi Road, Bangkok 10400, Thailand.

This article contains supporting information online at www.pnas.org/cgi/content/full/0806490106/DCSupplemental.

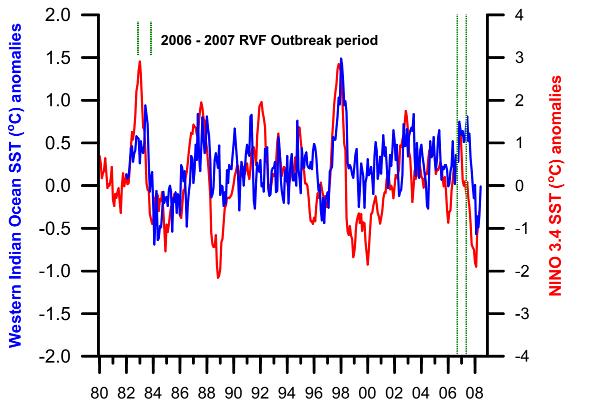

Fig. 1. Time series plot of western equatorial Indian Ocean (WIO) (10°N–10°S, 40°–64°E) and equatorial eastern-central Pacific Ocean SST (NINO, 3.4: 5°N–5°S, 170°W–120°W) anomalies. Anomalies are depicted as degree Celsius departures from their respective climatological baseline periods. Convergence of anomalous positive SSTs between the 2 regions is associated with above-normal rainfall over the RVF endemic region of the Horn of Africa.

are collected daily by several satellites in an ongoing fashion as part of the global climate observing efforts of NASA and the National Oceanic and Atmospheric Administration.

Results and Discussion

The development of warm ENSO conditions, indicated by anomalous warming of SSTs (>1 °C) in the eastern-central Pacific region and the concurrent anomalous warming of SSTs (>0.5 °C) (2) in the western equatorial Indian Ocean region (Fig. 1) during the September 2006 to November 2006 period (Fig. 2), enhanced precipitation over the central and eastern Pacific and the Western Indian Ocean (WIO) extending into the Horn of Africa. These anomalous patterns of precipitation are evident in outgoing longwave radiation (OLR), often used as a proxy for large-scale convection and rainfall in the tropics (Fig. 3 and Fig. S3) (16). Persistent anomalous positive SSTs in the WIO, and central and eastern Pacific, beginning in August 2006 resulted in above-normal precipitation manifested by negative anomalies in OLR (-20 to -80 W/m^2) (Fig. 3). For the Horn of Africa, seasonal total rainfall for the September–November 2006 short-rains season exceeded ≈600 mm in some locations (Fig. S3), resulting in excess rainfall amounts on the order of ≈400 mm during the same period (Fig. 4). Most of this rainfall fell over RVF endemic areas in this region. As during previous periods of elevated and widespread rainfall, the excess rainfall resulted in anomalous vegetation growth, with departures ranging between 20 and 100% above normal (Fig. 5), as illustrated by satellite derived NDVI anomalies (12, 24).

Persistence of elevated and widespread rainfall resulted in abundant vegetation growth from September through December 2006, and created ideal conditions for the flooding of dambo

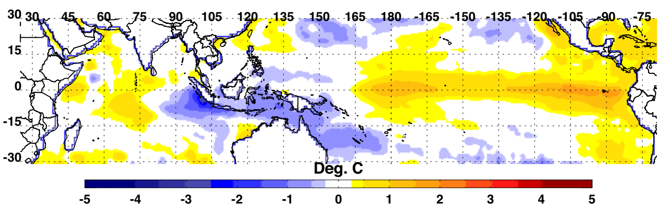

Fig. 2. Seasonal global tropical SST anomalies for September to November 2006 expressed in degrees Celsius with respect to the 1982–2006 base mean period. Positive anomalies in the equatorial eastern-central Pacific Ocean are a manifestation of the 2006–2007 warm ENSO event.

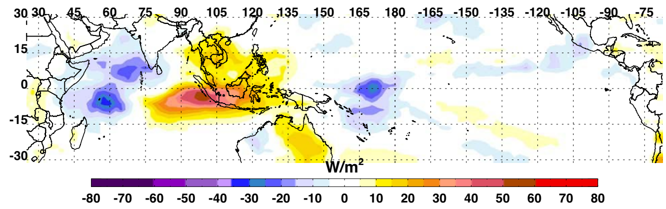

Fig. 3. Seasonal global tropical OLR anomalies (watts per square meter) for September to November 2007 computed with respect to the 1979–2006 base mean period. Negative OLR anomalies are an indicator of convective activity associated with positive SST anomalies in the western equatorial Indian Ocean and the equatorial eastern-central Pacific Ocean regions. Positive OLR anomalies are indicative of severe drought conditions in Southeast Asia.

formations, which serve as mosquito habitats in this region. Dambos are low-lying areas that flood in the wet season and form an essential part of the soil catenas in East and Southern Africa (20). The flooding of dambos induces the hatching of transovarially infected *Aedes mcintoshi* mosquito eggs that are dormant in the soil, producing infected adult females in 7–10 days that can transmit RVF virus to domestic animals (1, 22, 25). After a blood meal, the *Aedes* mosquitoes will lay infected eggs on moist soil at the edge of mosquito habitats, but appear to not be an efficient secondary vector of the virus between infected and noninfected domestic animals and humans (25, 26). However, *Culex* species mosquito vectors subsequently colonize these flooded dambos and, with a delay of several weeks, large populations of these mosquitoes emerge and efficiently transmit the virus from domestic animals, which amplify the virus, to noninfected domestic animals and humans (22, 25, 26). By using information gained from previous RVF outbreaks (2, 12, 25, Fig. S2) and the analysis of satellite data, we mapped areas at elevated risk of RVF activity and issued monthly early-warning advisories over the Horn of Africa region starting in September 2006 (15, 16).

Our RVF risk mapping method is first set in motion by the concurrently warmer SSTs in the central and eastern Pacific, and in the western equatorial Indian Ocean of >1 °C and >0.5 °C, respectively. Historical observations and experience have shown that these concurrently warmer SSTs are leading indicators of excessive rainfall in the Horn of Africa and, thus, elevated risk

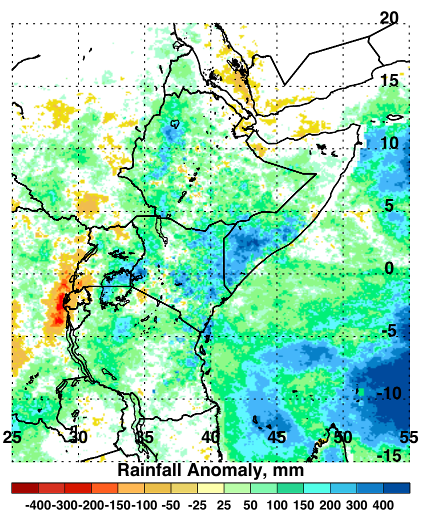

Fig. 4. Seasonal rainfall anomalies in millimeters for the Horn of Africa from September to November 2006. The anomalies are computed as deviations from the long-term seasonal mean for the period 1995–2006. RVF endemic areas of the Horn of Africa, especially eastern Kenya and Somalia, received an excess of +400 mm of rainfall during this 3-month period.

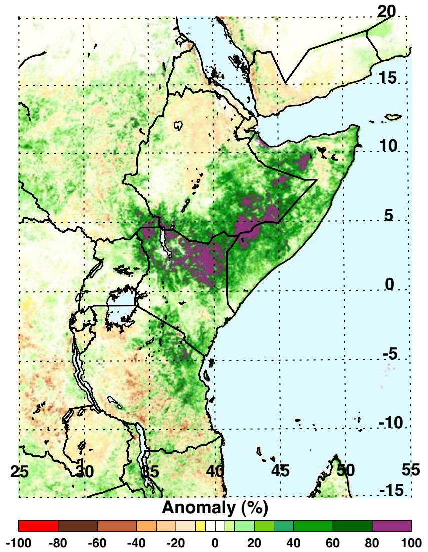

Fig. 5. NDVI anomalies for December 2006. NDVI anomalies are computed as percentage departures from the 1998–2006 mean period. Positive anomalies are associated with above-normal rainfall and are indicative of anomalous vegetation growth, creating ideal eco-climatic conditions for the emergence and survival of large populations of RVF mosquito vectors from dambo habitats.

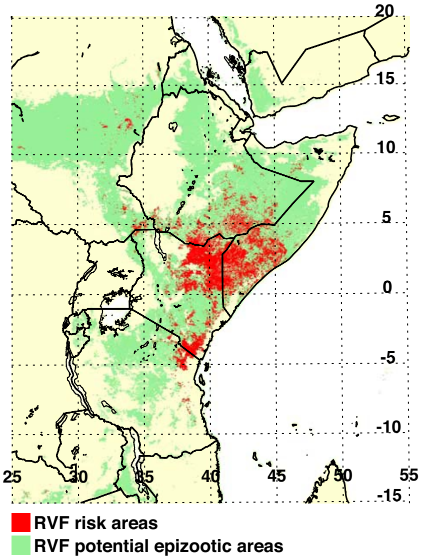

Fig. 6. RVF calculated risk map for December 2006 for the Horn of Africa. The areas shown in red represent areas of persistent rainfall and vegetation growth from October through December, where potential RVF infected mosquitoes could emerge and transmit the virus to livestock and human populations.

of RVF activity in that region (2, 12). To identify specific areas in the Horn of Africa where excessive rainfall occurs, we use NDVI time series data as a surrogate for rainfall and ecological dynamics. These areas are defined by mean annual NDVI values ranging between 0.15 and 0.4 and mean annual total rainfall ranging between 100 and 800 mm (Fig. S4 and *SI Materials and Methods*) (12). The persistence of greener-than-normal conditions over a 3-month period in the endemic region identifies areas with ideal ecological conditions for mosquito vector emergence and survival (*SI Materials and Methods*) (12). Based on the presence and persistence of anomalous green vegetation from October through December 2006, most of the central Rift Valley, eastern and north-eastern regions of Kenya, southern Ethiopia, most of central Somalia, and northern Tanzania were identified as areas at elevated risk for RVF outbreaks (Fig. 6). Such maps are routinely produced every month to guide vector and disease surveillance in the region. By using our early warning advisories issued in early November 2006 of the elevated risk of RVF outbreaks (15), the Department of Defense–Global Emerging Infections Surveillance and Response System and the Department of Entomology and Vector-borne Disease, United States Army Medical Research Unit-Kenya initiated entomological surveillance in Garissa, Kenya, in late November 2006, weeks before subsequent reports of unexplained hemorrhagic fever in humans in this area.

The first human cases of RVF in Kenya were reported from Garissa in mid-December 2006, with the index case in Garissa having an estimated onset date of 30 November 2006 (27). The disease was initially identified by reports of abortions in domestic animals, followed by observation of clinical signs and symptoms in humans, and then by detection of RVF virus or detection of RVF specific antibody. In general, although false positives of particular human or animal specimens can occur, false reporting of a RVF case after appropriate laboratory confirmation was not reported during this outbreak (28). The early warning enabled the government of Kenya, in collaboration with the World Health Organization, the United States Centers for Disease Control and Prevention, and the Food and Agricultural Organization of the United Nations to mobilize resources to implement disease mitigation and control activities in the affected areas, and prevent its spread to unaffected areas.

The evolution of rainfall over the Horn of Africa during December 2006 to March 2007 followed the movement of the Intertropical Convergence Zone into the southern hemisphere. From December 2006 through March 2007, most of the rainfall was concentrated over Tanzania and southwards (*SI Materials and Methods* and Fig. S5). By using combined information on risk mapping from December 2006 to January 2007, we issued another alert on the potential of RVF activity in northern Tanzania (*SI Materials and Methods* and Fig. S6). From mid to late January 2007, there were reported cases of RVF in the Arusha region of northern Tanzania (28, 29), including human hospital cases and disease in domestic animal populations. By mid-February 2007, 9 out of 21 administrative regions of Tanzania had reported cases of RVF in both livestock and human populations (27). The outbreak tapered off with the waning of the warm ENSO event (Fig. 1) and subsequent reduction in rainfall and drying conditions over most of the Horn of Africa region during the March-May 2007 period (*SI Materials and Methods* and Fig. S7, Fig. S8). There were reported human cases of RVF in Burundi in mid-May 2007, thought to have resulted from the consumption of infected animals imported from Tanzania (29). This mechanism of transmission emphasizes the importance of timely early warning with geographic specificity of RVF outbreaks to stop the export of potentially infected livestock to areas where the disease is not present.

In contrast to the 1997–1998 outbreak (4), the early warning described here for late 2006 and early 2007 enabled vector and disease surveillance activities to be initiated in Kenya and Tanzania 2 to 6 weeks before the human disease cases were identified. After the early identification of RVF transmission between the end of November and early December 2006 in Kenya, enabled by the early warning, subsequent enhanced surveillance activities and additional mitigation activities were implemented, including animal movement restrictions/quarantines, distribution of mosquito nets, social mobilization and dissemination of public information related to reducing human contact with infected animal products and mosquito vectors, and

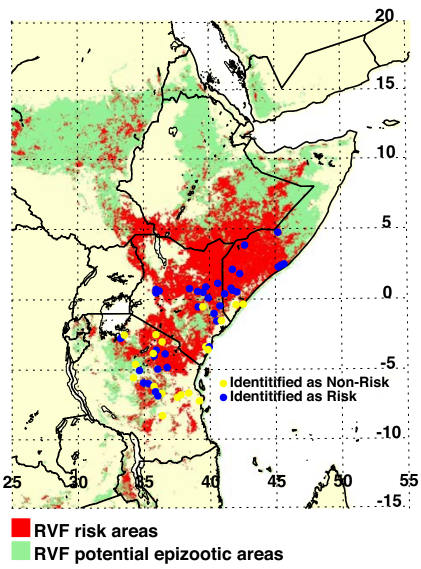

Fig. 7. Overall RVF risk areas shown in red for the period September 2006-May 2007 with human case locations depicted by blue and yellow dots. Blue dots indicate areas of RVF human case locations that were mapped to be within the risk areas (red) and within the potential epizootic area (green). Yellow dots represent human case locations outside the risk areas; 64% of all human cases fell within the areas mapped to be at risk to RVF activity during this period.

specific domestic animal vaccination and mosquito control programs in at-risk areas. Starting in mid-December 2006, most of the reported human RVF cases were from eastern Kenya, especially the Garissa and Ijara districts (Figs. S8 and S9), with limited reports from Somalia, and no reports from southern Ethiopia. This lack of disease surveillance information from Somalia and southern Ethiopia was not surprising, given an ongoing conflict between Ethiopia and Somalia at this time (28).

From December 2006 to May 2007, RVF human cases were reported in Somalia (114 cases reported, 51 deaths), Kenya (684 cases reported, 155 deaths), and Tanzania (290 cases reported, 117 deaths) (28). A postoutbreak mapping of human case locations on the aggregate potential RVF risk map from September 2006 to May 2007 found 64% of the cases were reported in areas mapped to be at risk within the RVF potential epizootic area, whereas 36% were reported in adjacent areas not mapped to be at risk of RVF activity (Fig. 7). However, the spatial distribution of these case locations shows that most of the cases in nonrisk areas were in close proximity (< 50 km) to areas mapped to be at risk. Thus, we are confident that most of the initial RVF infection locales were identified.

We hypothesize that the disease outbreak was more widespread than reported, because of civil and military conflicts in the region (especially in Somalia) and limited health infrastructure in many locales. Our risk mapping predictions performed better in Kenya and Somalia than in Tanzania. This asymmetry in the performance of predictions could be due to several factors, including: (*i*) misclassification of the potential RVF epizootic area in Tanzania and coastal Kenya, so that areas prone to RVF activity may not have been included; and (*ii*) delayed disease control response to the outbreak in Tanzania, with movement of animal and human cases outside of the affected areas. Large areas of Somalia have been subject to civil conflict over the last several years, and there is no government infrastructure in place to collect epidemiological data. Also, a number of areas in northern and eastern Kenya were inaccessible under widespread flood conditions, and there were no reports from southern Ethiopia.

Conclusion

This report documents a prospective operational prediction of a RVF outbreak in animals and humans. As in previous RVF outbreaks in the Horn of Africa (Fig. S2), the convergence of ENSO conditions in the eastern Pacific and concurrent warming of SSTs in the western equatorial Indian Ocean region was the trigger mechanism behind this outbreak. The late 2006-early 2007 outbreak adds to the historical evidence that interannual climate variability associated with ENSO has a large influence on RVF outbreaks in the Horn of Africa through episodes of abnormally high rainfall there. This analysis demonstrates that satellite monitoring and mapping of key climate conditions and land surface ecological dynamics (Fig. S9) are an important and integral part of public health surveillance and can help reduce the impact of outbreaks of vector-borne diseases such as RVF. This is one of many societal benefits that result from a robust earth observing system that monitors key climate variables in a systematic and sustained fashion.

Methods

We mapped and analyzed global satellite-derived time series measurements of SSTs, OLR, rainfall, and the NDVI. Indices of SSTs extracted from the eastern-central equatorial Pacific Ocean and the western equatorial Indian Ocean were used as leading indicators to show that interannual variability in SSTs associated with ENSO is an important factor driving the atmospheric response, as manifested by OLR and rainfall anomaly patterns. The land surface response to these variations in rainfall was captured through NDVI, with greener-than-normal conditions indicative of above-normal rainfall and vice versa. All data were converted into anomaly metrics expressed as differences of monthly measurements from their respective long-term mean values. The combination of excess and widespread rainfall and anomalous vegetation growth (Figs. S8 and S9) created ideal conditions for the emergence of RVF virus-carrying mosquito vectors from flooded habitats known as dambos in the Horn of Africa. The RVF risk mapping algorithm captured the persistence in greener-than-normal conditions over a 3-month period to identify areas with conditions for potential RVF activity in the RVF potential epizootic/epidemic areas within the Horn of Africa region. These mapped risk data were provided as early warning information to concerned agencies to guide vector surveillance and control, and to structure other mitigation activities. The risk mapping was implemented dynamically by using a 3 month moving window with early warnings issued routinely every month to keep track of changing climatic and ecological conditions, and consequently the changing nature of areas at risk for RVF activity in the disease endemic region through time.

For detailed data sources, methods, and analysis descriptions, see *SI Materials and Methods*.

ACKNOWLEDGMENTS. We thank the contributions of the United States Army Medical Research Unit-Kenya, the World Health Organization Department of Epidemic and Pandemic Alert and Response, the Food and Agricultural Organization of the United Nations, The United States Department of Agriculture Foreign Agricultural Service, and the Centers for Disease Control and Prevention. This work and project is supported in part by the Department of Defense Global Emerging Infections Surveillance and Response System and the United States Department of Agriculture–Agricultural Research Service.

1. Linthicum KJ, Bailey CL, Davies FG, Tucker CJ (1987) Detection of Rift Valley fever viral activity in Kenya by satellite remote sensing imagery. *Science* 235:1656–1659.
2. Linthicum KJ, *et al.* (1999) Climate and satellite indicators to forecast Rift Valley fever epidemics in Kenya. *Science* 285:397–400.
3. Davies FG, Linthicum KJ, James AD (1985) Rainfall and epizootic Rift Valley fever. *Bull WHO* 63:941–943.
4. Woods CW, *et al.* (2002) An outbreak of Rift Valley fever in northeastern Kenya, 1997–1998. *Emerg Infect Dis* 8:138–144.
5. Little PD, Teka T, Azeze A (2001) *Cross-Border Livestock Trade and Food Security in the Horn of Africa: An Overview* (USAID/REDSO, Washington, DC).
6. Nicholls N (1986) A method for predicting Murray Valley encephalitis in southeast Australia using the Southern Oscillation. *Aus Exp Biol Med Sci* 64:587–594.
7. Nicholls N (1993) El Nino-southern oscillation and vector-borne disease. *Lancet* 342:1284–1285.
8. Baylis M, Mellor P, Meiswinkel R (1999) Horse Sickness and ENSO in South Africa. *Nature* 397:574.

9. Woodruff R, *et al.* (2002) Predicting Ross River virus epidemics from regional weather data. *Epidemiology* 13:384–393.
10. Bouma JM, Dye C (1997) Cycles of malaria associated with El Niño in Venezuela. *JAMA* 278:1772–1774.
11. Kovats R, Bouma M, Hajat S, Worrall E, Haines A (2003) El Niño and Health. *Lancet* 362:1481–1489.
12. Anyamba A, Linthicum KJ, Mahoney R, Tucker CJ (2002) Mapping potential risk of Rift Valley fever outbreaks in African savannas using vegetation index time series data. *Photogramm Eng Rem S* 68:137–145.
13. Logan TM, Linthicum KJ, Davies FG, Binepal YS, Roberts CR (1991) Isolation of Rift Valley fever virus from mosquitoes collected during an outbreak in domestic animals in Kenya. *J Med Entomol* 28:293–295.
14. Logan TM, Davies FG, Linthicum KJ, Ksiazek TG (1992) Rift Valley fever antibody in human sera collected after an outbreak in domestic animals in Kenya Trans. *R Soc Trop Med Hyg* 86:202–203.
15. Anyamba A, *et al.* (2006) *Emergency Prevention System for Trans-boundary Animal and Plant Pests and Diseases (EMPRES)*, Food and Agricultural Organization of the United Nations, Available at http://www.fao.org/docs/eims/upload//217874/EW_hornafrica_nov06_Rift Valley fever.pdf; and Rift Valley Fever Monitor at http://www.geis.fhp.osd.mil/GEIS/SurveillanceActivities/RVFWeb/indexRVF.asp.
16. Anyamba A, Chretien JP, Small J, Tucker CJ, Linthicum KJ (2006) Developing climate anomalies suggest potential disease risks for 2006–2007. *Int J Health Geog* 5, 60, doi: 10.1186/1476–072X-5–60. Available at http://www.ijhealthgeographics.com/content/5/1/60/abstract.
17. Tucker CJ, Hielkema JU, Roffey J (1985) The potential of satellite remote sensing of ecological conditions for survey and forecasting desert-locust activity. *Int J Rem Sens* 6:127–138.
18. Hielkema JU, Roffey J, Tucker CJ (1986) Assessment of ecological conditions associated with the 1980/1981-desert locust plague upsurge in West Africa using environmental satellite data. *Int J Rem Sens* 7:1609–1622.
19. Linthicum KJ, *et al.* (1990) Application of polar-orbiting satellite data to detect Rift Valley fever vector mosquito habitats in Kenya. *Med Vet Entomol* 4:433–438.
20. Boast R (1990) Dambos: A review. *Prog Phys Geogr* 14:153–177.
21. Linthicum KJ, Davies FG, Bailey CL, Kairo A (1983) Mosquito species succession dambo in an East African forest. *Mosq News* 43:464–470.
22. Linthicum KJ, Davies FG, Bailey CL, Kairo A (1984) Mosquito species encountered in a flooded grassland dambo in Kenya. *Mosq News* 44:228–232.
23. Tucker CJ (1979) Red and photographic infrared linear combinations for monitoring vegetation. *Rem Sens Environ* 8:127–150.
24. Anyamba A, Tucker CJ, Mahoney R (2002) El Niño to La Niña: Vegetation response patterns over East and Southern Africa during 1997–2000 period. *J Climate* 15:3096–3103.
25. Linthicum KJ, Davies FG, Kairo A, Bailey CL (1985) Rift Valley fever virus (family Bunyaviridae, genus *Phlebovirus*): Isolations from Diptera collected during an interepizootic period in Kenya. *J Hyg* 95:197–209.
26. Turell MJ, *et al.* (2007) Vector competence of selected African mosquito (Diptera: Culicidae) species for Rift Valley fever Virus. *J Med Entomol* 45:102–108.
27. Nguku P, *et al.* (2007) Rift Valley Fever Outbreak – Kenya, November 2006–January 2007. *Mort Morb W Rep* 56:73–76. Available at http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5604a3.htm.
28. WHO (2007) *W Epi Rec* 82:69–180.
29. ProMed Mail (2007) *Rift Valley fever, East Africa*, archive no. 20070519.1592. Available at http://www.promedmail.org. Accessed 19 May, 2007.

SUSTAINABILITY SCIENCE